Characterization of Metallic Thin Film Growth by STM†

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Over the past several years, metallic multilayer systems have emerged as an important new area of research from the perspective of both fundamental science and technology. For example, magnetic multilayer systems exhibit a giant magnetoresistance (GMR) which is currently being exploited to develop superior read heads for magnetic recording. From the fundamental science viewpoint, a basic understanding of this phenomenon is lacking and represents both an experimental and theoretical challenge. A significant aspect of the challenge is that the final properties of multilayer systems depend strongly on structural details such as layer uniformity and interfacial structure, and therefore an understanding of the magnetic properties requires detailed characterization of and control over thin film growth. Scanning tunneling microscopy (STM) can be used to directly evaluate thin film morphology and is an ideal tool for determining growth processes in these systems. By using STM to study the growth of both Fe and Cr on Fe(001) substrates, we have made significant progress in the determination of fundamental growth processes in metallic systems. We have also correlated STM-determined details of the Cr/Fe interface with the magnetic properties of Fe/Cr/Fe multilayer systems to understand the relationship between magnetic properties and structure.

In the fundamental growth studies, we have characterized the temperature dependence of Fe(001) homoepitaxy from the nucleation of atomic-layer islands through the evolution of the growth of a thin film. In the early stages of growth, the density of the atomic-layer islands is found to be a strong function of temperature [1]. This results from the temperature dependence of the adatom diffusion and the critical atomic size of stable island formation, both of which can be determined from a statistical analysis of the 2-d nucleated islands [2]. As growth proceeds, we have shown that the film morphology is determined by step-edge barriers for diffusing adatoms [3]. At low temperatures where adatoms have insufficient energy to overcome the step-edge barriers, additional islands nucleate on existing islands resulting in a film morphology determined by the island density in the early stages of growth. This leads to rough surfaces with several layers in the growth front and damped RHEED intensity oscillations measured during growth as shown in Fig. 1 (a) and (b). Layer-by-layer growth is achieved at higher temperatures where the adatom thermal energies are sufficient to overcome the step-edge barriers. The characteristic persistent RHEED intensity oscillations measured during layer-by-layer growth are shown in Fig. 1 (c) along with the STM image of the surface after growth was stopped. To gain a full theoretical understanding of the growth process, a simulation of film growth has been achieved in a continuum growth model.

To correlate the STM-determined structure of Cr/Fe thin film systems with the magnetic properties, we use scanning electron microscopy with polarization analysis (SEMPA) to evaluate the exchange coupling in similarly prepared Fe/Cr/Fe multilayers [4]. In this system, the magnetic coupling of the two Fe layers oscillates between ferromagnetic and antiferromagnetic coupling with increasing thickness of the Cr spacer layer. The thickness dependence of the coupling is evaluated by depositing a wedge of Cr for the spacer layer and then exploiting the spatial resolution of SEMPA to determine the magnetization of the top Fe film along the wedge. Two periods of oscillation with thickness are observed in the Fe/Cr/Fe(001) system. The dominant period is found to depend on the Cr growth temperature. By using STM to evaluate the temperature dependence of the Cr film morphology, the observed strengths of the oscillation periods in the exchange coupling are seen to be a result of the roughness, or thickness fluctuations, of the Cr spacer layer.

Another consequence of the structural details of the Fe/Cr/Fe(001) system is seen in the exchange coupling measurements in the thin-Cr layer limit. The exchange oscillations with Cr thickness are not seen for thicknesses less than ~5 monolayers and the sign of the first oscillation is opposite to expectations. STM investigations of the early stages of Cr growth on Fe(001) show that the Cr alloys with the Fe substrate and that this interdiffusion persists for several layers of Cr deposition. For Cr coverages less than a monolayer, the alloy is seen as a low concentration of single impurity atoms embedded in the surface layers. The dominant element at the surface can be identified as Fe and the impurity atoms as Cr by using tunneling spectroscopy; a surface state near the Fermi energy on the Fe(001) surface leads to narrow peak in the tunneling conductance spectra and this conductance peak is seen on the alloyed surface between the single impurity atoms. As the initial Cr coverage is increased, the Fe concentration in the surface layers decreases. Chromium becomes the dominant element in the surface layers only after deposition of somewhere between 5 to 10 monolayers of Cr.

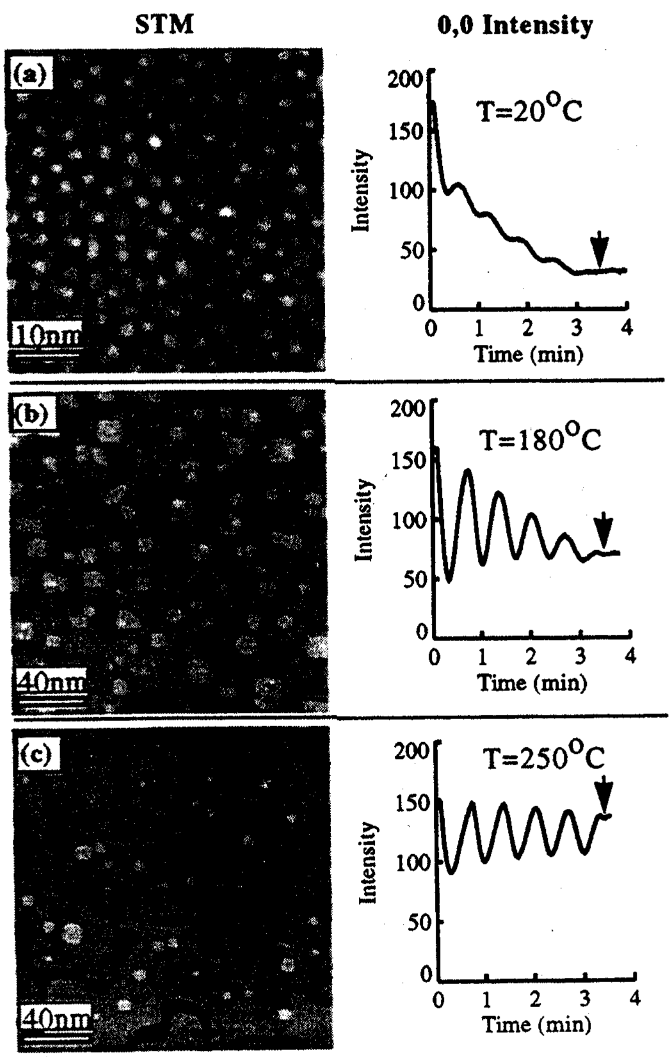

FIG. 1. STM and RHEED (0,0) beam intensity measurements of Fe on Fe(001) growth obtained on the same samples. All of the films were grown for five RHEED oscillations, at which time the Fe flux was turned off, indicated by the arrows in the RHEED plots. Sample temperatures during growth are (a) 20 °C, (b) 180 °C and (c) 250 °C. STM images are shown in a grey scale with black corresponding to the lowest height level. The major changes in grey level indicate monatomic steps.

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[1] J. A. Stroscio, D. T. Pierce and R. A. Dragoset, Phys. Rev. Lett. 70, 3615 (1993).
[2] J. A. Stroscio and D. T. Pierce, Phys. Rev. B 49, 8522 (1994).
[3] To be published.
[4] D. T. Pierce, J. A. Stroscio, J. Unguris and R. J. Celotta, Phys. Rev. B 49, 14564 (1994).